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M.S. Dresselhaus and G. Dresselhaus

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A summary of work carried out under the entire duration of this contract on "Fundamental Studies of Near Surface Modification of Carbon Fibers" from 9/1/85 to 4/30/90 is presented.

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Final Report
to the
Air Force Office of Scientific Research
for research on

Fundamental Studies of Near Surface Modification of Carbon Fibers

AFOSR Contract #F49620-85-C-0147
for the period
September 1, 1985 — April 30, 1990

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June 13, 1990

QUALITY INSPECTED 4

1 Overview

This final report starts with a restatement of the proposed research under the contract and is followed by a report on the research progress made during the period of this contract, September 1, 1985 – April 30, 1990. The coupling activities are tabulated in this report only for the August 1, 1989 – April 30, 1990 period, with tabulations for previous years found in the semiannual reports for each of the prior funding periods.

1.1 Abstract of Objectives

A research program is proposed relevant to the utilization of new technological developments for the modification of the near-surface region of graphite. These new technological developments include intercalation, ion implantation, pulsed laser irradiation by itself or coupled with ion implantation, and implantation-enhanced intercalation. The applications of these technologies are directed toward:

1. enhancing the adhesion of graphite-fibers to the matrix material of carbon-carbon composites,

2. retarding the oxidation of graphite fibers under high temperature operation,

3. enhancing the matching of the coefficient of thermal expansion of the graphite fibers to that of the matrix material and

4. improving the high temperature performance of graphite fibers more generally.

To achieve these objectives, fundamental studies must be undertaken, since almost nothing is known about the structure-property relationships of the surface modifications caused by use of these new technologies for the conditions of temperature and chemical environment pertinent to the applications proposed here. Secondly, since almost all previous work using these technologies has been done on bulk graphite, application of these technologies to graphite fibers must be explored, including the dependence of fiber morphology on the resulting structure-property relationships. A research program explicitly designed to achieve these objectives has been undertaken.

1.2 Statement of Work

Statement of work in AFOSR Contract #F49620-85-C-0147 on "Fundamental Studies of Near Surface Modification of Carbon Fibers".

- Derive and characterize parameters controlling modification of the near surface region of carbon fibers by ion implantation.
- Derive implantation conditions which enhance adhesion of graphite fibers to the matrix materials.
- Derive implantation conditions which retard oxidation rates of graphite fibers at high temperature.
- Derive surface modification approaches to match the coefficient of thermal expansion of the graphite fibers to the host material.
- Investigate modifications of the near surface region of graphite fibers by pulsed high energy density lasers.
- Derive surface modifications to enhance high temperature stability of graphite fibers by implantation, annealing, and high energy density laser irradiation.
- Investigate defect structures of ion implanted fibers by transmission electron microscopy.
- Investigate oxidation rate of carbon fibers under variation of pertinent implantation parameters, such as ion species, energy and fluence, temperature of implantation and temperature of annealing.
- Investigate the potential of the implantation-enhanced intercalation phenomena for controlled surface modification and enhancement of surface properties.
- Investigate the potential of the pulsed high power density laser phenomena for controlled surface modification and recrystallization.

2 Current Status of Research Effort

This final report presents a summary of the research progress made during the entire period of this contract (for the four year funding period and six months no-cost extension September 1, 1985 – April 30, 1990) on "Fundamental Studies of Near Surface Modification of Carbon Fibers". In presenting the summary, we refer by number (#n) to the publications which are listed in section 3.1 of this report.

2.1 Structure–Properties Measurements on Pristine Fibers

In studies of ways to characterize the various pristine carbon fibers, we have been engaged in a number of projects. The favorable fiber geometry was exploited (#5) to show that the temperature dependence of the thermal conductivity of carbon fibers could provide information on the amount of disorder. The temperature and magnetic field dependence of the negative magnetoresistance in disordered carbon fibers was investigated (#4, #10) and calculations based on the Bright model were carried out to explain these results. Subsequently it was found that weak localization effects in a magnetic field could provide a more coherent explanation for a large amount of magnetoresistance data exhibiting complicated temperature and magnetic field dependences. Quantitative studies were carried out to show that the degree of order in thick vapor grown carbon fibers was greater than for thin fibers (#2, #23).

Photoconductivity measurements were shown to provide a sensitive characterization tool for disordered carbon fibers (#9), though no in-depth study of this phenomenon was carried out. The Raman effect was used to characterize the amount of stress on a carbon fiber (#14, #18) by measurement of the shift of the peak frequency with stress for light polarized parallel and perpendicular to the fiber axis (stress direction).

From a scientific standpoint, the carbon fiber geometry and the availability of fibers with different electrical resistivities were exploited to make quantitative studies of the conductivity of liquid carbon (#16). The results of running a high current pulse through very thin fibers demonstrated that liquid carbon is metallic.

High resolution transmission electron microscopy was used to gain information on the degree of graphitization (#24, #29, #34) and the results were modeled on the basis of a thermodynamic model. The work on carbon fibers was subsequently extended to model carbon blacks (#34).

2.2 Structure–Properties Measurements on Other Carbons

In the course of our studies on the structural and electronic properties of carbon fibers, we typically use carbon materials standards for comparison to the fibers under study. We also use techniques developed for the characterization of fibers to study new, unexplored phenomena, generally in order to gain insight into the measured properties of disordered fibers. In this connection modeling of the electrical conductivity has been done for the transport properties of thin pregraphitic films (#11, #13).

Using transport and Raman measurements to study carbon-carbon composites, the properties of the embedded carbon fibers and of the surrounding matrix material could be measured independently (#17). Such information is of considerable interest for the characterization of materials with coexisting phases on a scale of several microns. Also in the area of optical techniques, we have used pulsed laser irradiation to introduce lattice defects or at high irradiation levels to produce liquid carbon. Our recent laser studies (#37) have been focused on studying the microstructure of liquid carbon after rapid solidification.

2.3 Structure–Properties Measurements on Related Materials

With regard to the BN host material, which has a very similar crystal structure to graphite, but is a wide gap semiconductor, we have managed to achieve intercalation using potassium and have even observed some in-plane ordering of the K intercalate relative to the BN host material (#27, #35). Another somewhat related material is C-BN which is a mixture of the C and BN constituents. By varying the relative amounts of C and BN, it is possible to vary the electrical properties over wide ranges. In our recent studies on BN (#26, #28, #36), the structure and properties of this material have been studied, correlated and modeled as a function of the fractional carbon content.

2.4 Structure–Properties Measurements on Intercalated Fibers

A main thrust of our studies on carbon fibers has been on the structure-properties relationships of intercalated carbon fibers in their own right and in comparison with bulk host materials. In one study, the thermal conductivity of intercalated carbon fibers was measured as a function of temperature (#1) to determine the dominant thermal conduction mechanisms. The Raman effect was used to characterize fibers along their length using a Raman microprobe (#3), or for specific intercalated species (AsF_5) to compare with measurements by other techniques (#32). The exfoliation of carbon fibers was examined (#7) in order to find the relation of this effect in fibrous to that in bulk intercalation compounds. The microstructure of these intercalated fibers was investigated to gain further understanding of the intercalation process and of the graphitization process itself (#8, #23). For practical utilization of intercalated carbon fibers, the bromine intercalation process was studied with regard to intercalation-enhanced conductivity, temporal and thermal stability and current carrying capacity of the intercalated fibers (#23, #30, #31).

Our main scientific work involving intercalated carbon fibers is the study of the weak localization phenomenon in the fluorinated carbon fibers (#38). Our early work (#33) showed that for low fluorine concentrations the fluorine intercalate behaves similar to other acceptor intercalates, showing a large increase in the in-plane conductivity (along the fiber axis). At fluorine concentrations beyond C_6F, the electrical conductivity starts to decrease, reaching conductivities more than an order of magnitude lower than for the pristine fibers before intercalation. The effect is an order of magnitude

more pronounced in the fibers as compared with bulk compounds of similar stoichiometry. We have exploited the ability to control the lattice disorder through the amount of intercalate uptake as a means to study 2D weak localization effects quantitatively in the C_xF fibers. Because of the large magnitude on this effect in the C_xF fibers, this is an ideal system for the study of these 2D localization effects. The experimental techniques we have employed include the temperature dependence of the electrical conductivity, magnetoresistance, photoconductivity, thermal transport phenomena, and the Raman effect. This work is still in progress, especially study of transport phenomena in the transition between the weak localization and strong localization regimes.

2.5 Book

During the period of this contract a book on "Carbon Fibers and Filaments" was prepared and published (#15).

2.6 Review Articles

A number of review articles have been prepared (#6,#12,#19,#21,#24,#25).

A review of the properties of carbon fibers and filaments was first presented orally to researchers at the Aberdeen Proving Grounds (#6). The many questions and comments stemming from this talk and the talks given by our collaborators I.L. Spain and H. Goldberg indicated the need for a monograph for advanced students and researchers in the field. This review (#6) therefore led directly to writing a book with these same colleagues (#15).

A short review on the structure and properties of carbon fibers was prepared for a NATO summer school (held in Erice, Italy in 1988) and this review was published in the book of conference proceedings edited by M.S. Dresselhaus.

A review on liquid carbon was prepared on invitation by the Japanese Carbon Society (#19). A large part of this review is devoted to the formation of liquid carbon by the rapid passage of a large current through the carbon fiber (Joule heating). Measurements of the electrical resistivity vs. time are made, yielding a plot of resistivity vs. temperature. The most significant result of this work is to show that liquid carbon is metallic, and to determine many of the properties of this unusual liquid.

An invited review article on "New Trends in Intercalation Compounds" has been prepared (#21), in which some attention is given to the intercalation of fiber host materials. The overall objective of this work was to summarize recent advances in the field of intercalation, and in particular pointing to new research opportunities in the field.

An extensive invited review of intercalated carbon fibers has been completed and submitted for publication in a volume on graphite intercalation compounds to be published by Springer (#24). This represents a major expansion of the work previously published in 1988 by Springer as a chapter on our monograph volume on "Carbon Fibers and Filaments".

In addition, a lecture, a manuscript and classroom notes on carbon fibers and composites were prepared for the 1988 Enrico Fermi School on Solid State Physics (#25) held in La Spezia, Italy. The lecture on "Carbon Fibers and Composites" was one of four lectures presented at the Enrico Fermi School by M.S. Dresselhaus on the more general topic of Intercalation Compounds and composites.

3 Reports and Publications

3.1 Publications

1. **"The Effect of Intercalation on the Thermal Conductivity of Benzene–Derived Carbon Fibers"**, L. Piraux, B. Nysten, J. P. Issi, L. Salamanca-Riba, and M. S. Dresselhaus. *Solid State Commun.*, **58**, 265, (1986).

2. **"Size Effects in Electrical Properties of Benzene–Derived Graphite Fibers"**, M. Z. Tahar, M. S. Dresselhaus, and M. Endo. *Carbon*, **24**, 67, (1986).

3. **"Raman Microscopy of Intercalated Graphite Fibers"**, L. E. McNeil, J. Steinbeck, L. Salamanca-Riba, and G. Dresselhaus. *Carbon*, **24**, 73, (1986).

4. **"Magnetoresistance of Graphite Fibers"**, I. Rahim, K. Sugihara, M. S. Dresselhaus, and J. Heremans. *Carbon*, **24**, 663–669, (1986).

5. **"The Thermal Conductivity and Raman Spectra of Carbon Fibers"**, J. Heremans, I. Rahim, and M. S. Dresselhaus. *Phys. Rev.*, **B32**, 6742, (1985).

6. **"Small, Needle–Shaped Filaments Based on Carbon"**, M. S. Dresselhaus, H. A. Goldberg and I. L. Spain, in *Proceedings of the 1985 CRDC Scientific Conference on Obscuration and Aerosol Research*, R. H. Kohl, editor, volume I and II, pages 291–324.

7. **"Exfoliation of Benzene–Derived Graphite Fibers"**, H. J. Jiménez-González, J. S. Speck, G. Roth, M. S. Dresselhaus, and M. Endo. *Carbon*, **24**, 627, (1986).

8. **"Microstructure of Thin Intercalated Benzene Derived Graphite Fibers"**, E. Minami, X. Hao, J. S. Speck, M. S. Dresselhaus, and M. Endo. In M. S. Dresselhaus, G. Dresselhaus, and S. A. Solin, editors, *Extended Abstracts of the Symposium on Graphite Intercalation Compounds at the Materials Research Society Meeting, Boston*, page 213. Materials Research Society Press, Pittsburgh, PA, (1986).

9. **"Photoconductivity in Graphite Fibers"**, J. Steinbeck, M. S. Dresselhaus, G. Dresselhaus, and T. Venkatesan. In M. S. Dresselhaus, G. Dresselhaus, and S. A. Solin, editors, *Extended Abstracts of the Symposium on Graphite Intercalation Compounds at the Materials Research Society Meeting, Boston*, page 129. Materials Research Society Press, Pittsburgh, PA, (1986).

10. **"Anomalous Temperature-Dependent Negative Magnetoresistance in Pregraphitic Carbons"**, K. Sugihara and M. S. Dresselhaus. In M. S. Dresselhaus, G. Dresselhaus, and S. A. Solin, editors, *Extended Abstracts of the Symposium on Graphite Intercalation Compounds at the Materials Research Society Meeting, Boston*, page 135. Materials Research Society Press, Pittsburgh, PA, (1986).

11. **"Electron-Rayleigh Wave Interaction in Thin Film Carbons"**, K. Sugihara. In M. S. Dresselhaus, G. Dresselhaus, and S. A. Solin, editors, *Extended Abstracts of the Symposium on Graphite Intercalation Compounds at the Materials Research Society Meeting, Boston*, page 132. Materials Research Society Press, Pittsburgh, PA, (1986).

12. **"Intercalated Graphite Fibers"**, M. S. Dresselhaus. In M. S. Dresselhaus, editor, *Intercalation in Layered Materials*, page 461. Plenum Press, New York, (1987).

13. **"Electrical Conduction in Thin Film Carbons"**, K. Sugihara and M. S. Dresselhaus. In *Extended Abstracts of the 18^{th} Biennial Conference on Carbon*, page 421, (1987). July 19-24, 1987, Worcester Polytechnic Institute.

14. **"Stress Measurements in Graphite Fibers by Laser Raman Spectroscopy"**, H. Sakata, G. Dresselhaus, and M. Endo. In *Extended Abstracts of the 18^{th} Biennial Conference on Carbon*, page 18, (1987). July 19-24, 1987, Worcester Polytechnic Institute.

15. **"Graphite Fibers and Filaments"**, M. S. Dresselhaus, G. Dresselhaus, K. Sugihara, I. L. Spain, and H. A. Goldberg, volume 5 of *Springer Series in Materials Science*, Springer-Verlag, Berlin, (1988).

16. **"Observation of Metallic Conductivity of Liquid Carbon"**, J. Heremans, C. H. Olk, G. L. Eesley, J. Steinbeck, and G. Dresselhaus. *Phys. Rev. Letts.*, **60**, 452, (1988).

17. **"Electronic and Structural Studies of Carbon-Carbon Composites"**, G. L. Doll, R. M. Sakya, J. T. Nicholls, J. S. Speck, M. S. Dresselhaus, and G. B. Engle. *Synthetic Metals*, **23**, 481, (1988).

18. **"Effect of Uniaxial Stress on the Raman Spectra of Graphite Fibers"**, H. Sakata, G. Dresselhaus, M. S. Dresselhaus, and M. Endo. *J. Appl. Phys.*, **63**, 2769, (1988).

19. **"Liquid Carbon"**, M. S. Dresselhaus and J. Steinbeck. *Tanso*, **132**, 44, (1988). Journal of the Japanese Carbon Society.

20. **"Lattice Vibrations in Thin Film Carbons: I Electron-Rayleigh Wave Interaction"**, K. Sugihara. *Phys. Rev.*, **B37**, 7063, (1988).

21. **"New trends in intercalation compounds"**, M. S. Dresselhaus, *Mater. Sci. Eng.*, 1, 259, (1988). Section B: Solid State Materials for Advanced Technology.

22. **"Preparation and electrical properties of bromine intercalated vapor-grown carbon fibers"**, M. Endo, H. Yamanashi, G. L. Doll, and M. S. Dresselhaus, *J. Appl. Phys.*, (1988). 64, 2995.

23. **"Structure and intercalation of thin benzene derived carbon fibers"**, J. S. Speck, M. Endo, and M. S. Dresselhaus, *J. Crystal Growth* 94, 834 (1989).

24. **"Intercalation of Graphite Fibers"**, M. S. Dresselhaus and M. Endo, *Springer Proceedings in Physics*, Springer-Verlag, Berlin, (1988). Springer review article.

25. **"Intercalation compounds and composites"**, M. S. Dresselhaus, *Il Nuovo Cimento*, xxx, (1988). Enrico Fermi School.

26. **"Properties and characterization of co-deposited boron nitride and carbon materials"**, A. W. Moore, S. L. Strong, G. L. Doll, M. S. Dresselhaus, I. L. Spain, C. W. Bowers, J. P. Issi, and L. Piraux, *J. Appl. Phys.*, 65, 5109, (1989).

27. **"Intercalation of hexagonal BN with potassium"**, G. L. Doll, J. S. Speck, G. Dresselhaus, M. S. Dresselhaus, K. Nakamura, and S.-I. Tanuma. In M. Endo, M. S. Dresselhaus, and G. Dresselhaus, editors, *Extended Abstracts of the Symposium on Graphite Intercalation Compounds at the Materials Research Society Meeting, Boston*, page 133, Materials Research Society Press, Pittsburgh, PA, (1988).

28. **"Physical properties of co-deposited C-BN composites"**, A. W. Moore, S. L. Strong, G. L. Doll, M. S. Dresselhaus, J. P. Issi, and L. Piraux, In M. Endo, M. S. Dresselhaus, and G. Dresselhaus, editors, *Extended Abstracts of the Symposium on Graphite Intercalation Compounds at the Materials Research Society Meeting, Boston*, page 141, Materials Research Society Press, Pittsburgh, PA, (1988).

29. **"Graphitization of thin benzene derived carbon fibers"**, J. S. Speck, M. S. Dresselhaus, and M. Endo, In M. Endo, M. S. Dresselhaus, and G. Dresselhaus, editors, *Extended Abstracts of the Symposium on Graphite Intercalation Compounds at the Materials Research Society Meeting, Boston*, page 169, Materials Research Society Press, Pittsburgh, PA, (1988).

30. **"Intercalation and electrical properties of bromine intercalated vapor-grown graphite fibers – conductivity, and current carrying capacity"**, M. Endo, A. Sudou, H. Yamanashi, T. Inada, G. L. Doll, and M. S. Dresselhaus, In M. Endo, M. S. Dresselhaus, and G. Dresselhaus, editors, *Extended Abstracts of the Symposium on Graphite Intercalation Compounds: Science and Applications*, page 185, Materials Research Society, Pittsburgh, PA, (1988).

31. **"Intercalation and electrical properties of highly ordered graphite fibers"**, M. Endo, H. Yamanashi, A. Sudou, and M. S. Dresselhaus, In D. Guérard and P. Lagrange, editors, *International Colloquium on Layered Compounds*, page 169, (1988). Pont-à-Mousson Conference.

32. **"Raman and x-ray study of AsF_5/vapor grown graphite fibers"**, I. Ohana, M. S. Dresselhaus, and M. Endo, *Carbon*, **27**, 417, (1989).

33. **"Metal-nonmetal transition induced by reorientation of the fluorine molecules in stage-2 compounds of C_xF"**, I. Ohana, *Phys. Rev.* **B39**, 1914 (1989).

34. **"Thermodynamic calculations of the graphitization of carbon blacks"**, J. S. Speck, *J. Appl. Phys.*, **67**, 495, (1990).

35. **"Intercalation of hexagonal BN with potassium"**, G. L. Doll, J. S. Speck, G. Dresselhaus, M. S. Dresselhaus, K. Nakamura, and S. I. Tanuma, *J. Appl. Phys.*, **66**, 2554, (1989).

36. **"Thermal stability of co-deposited C-BN composites"**, A. W. Moore, S. L. Strong, G. L. Doll, and M. S. Dresselhaus. In *Extended Abstracts of the 19th Biennial Conference on Carbon*, page 514, (1989). July 19-24, 1989, State College of Pennsylvania.

37. **"Microstructural Studies of Laser Irradiated Graphite Surfaces"**. J. S. Speck, J. Steinbeck, and M. S. Dresselhaus. *J. Mat. Res.*, **5**, 980, (1990).

38. **"Electrical and Thermal Properties of Fluorine-Intercalated Graphite Fibers"**, L. Piraux, V. Bayot, J. P. Issi, M. S. Dresselhaus, M. Endo, and T. Nakajima. *Phys. Rev.*, **B41**, 4961, (1990).

3.2 Student Theses

- Ala Alryyes, MS in EECS, May 1988, "The Photoconductivity of Carbon Fibers".

- Patrick Berthier, MS in Materials Science and Engineering, August 1987, "Electrical Resistivity and Magnetoresistance of Benzene Derived Graphite Fibers at Low Temperature".

- Stanislas L. Divittorio, MS in Materials Science and Engineering, December 1989, "Weak Localization Studies in Graphite Fibers".

- Errol O. Grannum, BS in EE, June 1989, "Hydrogen Adsorption in Stage 2 Intercalated Pitch and Thin Vapor Grown Fibers at 77 K".

- J. Speck, Ph.D. in Materials Science and Engineering, August 1989, "Structural correlations in graphite and its layer compounds".

- J. Steinbeck, Ph.D. in Physics, August 1987, "Studies of the High Temperature Properties of Graphite and Liquid Carbon Using Pulsed Laser Heating".

- A. Thomas, MS in Physics, February 1990, "Magnetoresistance Measurements in Carbon/Carbon Composites".

3.3 Honors

- M.S. Dresselhaus, May 30, 1988, "Hund Klemm Lecture", at the Max Planck Institute in Stuttgart, West Germany.

- M.S. Dresselhaus, May 31, 1988, Doctorat Honoris Causa, Catholique Universite de Louvain, Louvain, Belgium.

- M.S. Dresselhaus, July, 1988, Enrico Fermi Lectures in La Spezia, Italy

- M.S. Dresselhaus, August 25, 1988, Kitagawa Summit Lectures in Tokyo, Japan.

- M.S. Dresselhaus, May 25, 1989, Hon. D. Sc. Rutgers University.

- M.S. Dresselhaus, February, 1988, Annual Achievement Award, Engineering Societies of New England.

- M.S. Dresselhaus, Institute Professor, 1985 present

- M.S. Dresselhaus, Visiting Professor, Department of Materials Science, The Technion, Israel Institute of Technology, Haifa, Israel, January 1990

- M.S. Dresselhaus, MIT Killian Faculty Award, 1986

- M.S. Dresselhaus, Phi Beta Kappa Lecturer, 1986 87

- M.S. Dresselhaus, Elected Member, Council of National Academy of Sciences, 1987 1990; Elected Chairman, Engineering Section, 1987 1990

- M.S. Dresselhaus, Member, Governing Board, National Research Council, 1984 87, 1989 90, Executive Committee of Governing Board, 1985 87

- M.S. Dresselhaus, Elected Member, Council, Materials Research Society, 1984 87, 1990 93.

- M.S. Dresselhaus, Principal Editor, Journal of Materials Research, 1988

- M.S. Dresselhaus, Member, Selection Committee for Packard Faculty Fellowships, 1988

- M.S. Dresselhaus, Member, Energy Research Advisory Board (ERAB), DOE, 1984 90; Chairman, ERAB Education Panel, 1987 88

- M.S. Dresselhaus, Chairman, JTEC Study for the NSF on *High Temperature Superconductivity in Japan*, 1989
- M.S. Dresselhaus, Member Board of Governors, Argonne National Laboratory, 1985–88; Member, Scientific and Technical Advisory Committee 1988–
- M.S. Dresselhaus, Elected Board of Directors, American Association for the Advancement of Science, 1985–89

4 Personnel Involved with Research Program

- Mildred S. Dresselhaus – *Principal Investigator*
  Responsible for the research and the direction of all aspects of this program on "Fundamental Studies on Near Surface Modification of Carbon Fibers".
- Gene Dresselhaus – *Co-Principal Investigator*
  Responsible together with the principal investigator for the research and the direction of all aspects of the program.
- A. Alryyes – Graduate *student*
  Responsible for studies of frequency dependence of photoconductivity of carbon fibers. Transferred to another research group after completion of MS Thesis.
- P. Berthier – Graduate *Student*
  Responsible for low temperature transport properties of benzene derived carbon fibers.
- S.L. Divittorio – Graduate Student
  Responsible for transport measurements in fluorinated carbon fibers and in activated carbon fibers.
- G. Doll – Research Associate
  Responsible for Raman characterization of carbon–carbon composites using Raman scattering and electrical resistivity measurements. Also responsible for intercalation of BN with K and for studies of the C-BN material.
- A. Fung – Graduate Student
  Responsible for Raman and magnetoresistance measurements in fluorinated carbon fibers and activated carbon fibers.
- K. Kuriyama – Visiting Scientist
  Responsible for photoconductivity studies on activated carbon fibers.
- I. Ohana – Research Associate
  Responsible for Raman characterization of intercalated carbon fibers, especially with AsF_5, for high electrical conductivity applications.

- A. Rao – Research Associate
  Responsible for Raman characterization of intercalated carbon fibers and activated carbon fibers.

- J. Speck – Graduate Student
  Responsible for high resolution transmission electron microscopy studies of graphite fibers and other relevant materials. Responsible for modeling the graphitization of very thin fibers.

- J. Steinbeck – Graduate Student
  Responsible for studies in liquid carbon and for photoconductivity studies in carbon fibers and disordered carbons.

- K. Sugihara – Research Associate
  Responsible for transport calculations in carbon fibers.

- A. Thomas – Graduate Student
  Responsible for magnetoresistance measurements on carbon-carbon composites.

4.1 Coupling Activities – Seminars and Invited Conference Papers

The MIT group is strongly coupled to international activities on carbon fibers and intercalated carbon fibers. Titles of the many seminars, invited talks and symposia given from September 1, 1985 – April 30, 1989 are listed in the previous seven semiannual reports. Below are listed titles of seminars, invited talks and symposia given from May 1, 1989 to April 30, 1990 relevant to the work supported under this contract.

- June 4, 1989; Meeting with Mr. K. Kuriyama and Prof. Endo in Tokyo to discuss research program on activated carbon fibers (MSD)

- June 28, 1989; Talk on "Thermal Stability of Co-deposited C–BN Composites", Penn State University, 19th Biannual Carbon Conference (GD)

- July 10, 1989; Discussions with Dr. D. Shafer at Sandia National Laboratory on carbon foams (MSD)

- July 28, 1989; Discussions with Prof. J.-P. Issi at MIT on transport properties of fluorinated carbon fibers (MSD and GD)

- August 23, 1989; Talk on "Recent Advances in Carbon Fiber Research , at Yazaki Research Laboratory, Mishima, Japan (MSD)

- August 24, 1989; Discussions with Professor T. Nakajima on the synthesis of fluorine intercalated fibers and research results obtained with these fibers (MSD and GD)

- August 26, 1989; Discussions with Professor T. Enoki on research results obtained with fluorinated carbon fibers and planned future research on activated carbon fibers.

- August 28, 1989; Talk on "Recent Advances in Carbon Fiber Research", at Shinko Research Laboratory, Nagano, Japan (MSD)

- August 29, 1989; Talk on "New Science using Carbon Fibers", Invited talk, Carbon Society of Japan (MSD)

- August 30, 1989; Talk on "Overview of Research on Graphite Intercalation Compounds including Fibrous Host Materials", at Iwaki Mesei University, Iwaki, Japan (MSD)

- September 5, 1989; Meeting and discussions with researchers working on Special MITI program on Graphite Intercalation Compounds and Carbon Fibers, chaired by Dr. Doi, Tokyo, Japan (MSD and GD)

- December 11, 1989; Discussions with Prof. Enoki and Dr. Suzuki at MIT on fluorinated carbon fibers (MSD and GD).

- January 10, 1990; Discussions with Prof. Davidov at Hebrew University, Jerusalem on fluorinated carbon fibers (MSD).

4.2 Collaborators

- Dr. H. Goldberg – Research Staff, Celanese Corporation.
  Collaborates on PAN fiber studies and review article.

- Dr. J. Heremans – Research Staff, General Motors Research Lab.
  Collaborates on high temperature conductivity studies of fibers and of liquid carbon.

- Dr. J. Perkins and Dr. L. Shepard – Army Materials Res. Center, Watertown, MA.
  Collaborates on development of transition metal intercalated graphite fibers.

- Prof. I.L. Spain – Professor of Physics, Colorado State Univ., Fort Collins, CO.
  Collaborates on fiber studies and review article.

- Dr. T. Venkatesan – Research Staff, Bell Commun. Research, Red Bank, NJ.
  Collaborates on pulsed laser irradiation studies of photoconductivity of graphite fibers.

- Dr. Arthur Moore, Union Carbide
  Collaborates on C-BN research.

- Professor M. Endo, Shinshu University
  Collaborates on carbon fiber research and supplies us with fiber samples and new carbon materials.

- G.B. Engle – Goodrich Corp., Santa Fe Springs, CA and
  Nuclear and Aerospace Materials Corp., Poway CA
  Collaborates on carbon-carbon composite studies.

5 New Discoveries, Patents or Inventions

none